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A MULTIDISCIPLINARY PROGRAM OF INVESTIGATION OF THE POSSIBILITY OF AN ELECTROMAGNETIC WAVE GUIDE IN THE LOWER CRUST

7 MARCH 1972

THE UNIVERSITY OF TEXAS AT DALLAS

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PREFACE

The program outlined in this report was prepared at a Multidisciplinary Workshop held under ONR-ARPA sponsorship at the Colorado School of Mines, February 14-16, 1972. It is a pleasure to acknowledge the assistance given to the workshop by the staff of the Department of Geophysics at the School of Mines. Special thanks are due to Dr. George Keller for arranging for the workshop to be held at the School of Mines.

MULTIDISCIPLINARY WORKSHOP

GOLDEN, COLORADO

FEBRUARY 14 - 16, 1972

PARTICIPANTS

Convenor: Dr. A. L. Hales, University of Texas at Dallas

Theoretical Studies

Chairman: Dr. James Wait, NOAA, CIRES, University of Colorado

Member: Mr. R. H. Baker, Massachusetts Institute of Technology

Laboratory Experiments

Co-Chairmen: Dr. Amos Nur, Stanford University
Dr. Gene Simmons, Massachusetts Institute of Technology

Members: Dr. M. J. Holdaway, Southern Methodist University
Dr. Theodore Madden, Massachusetts Institute of Technology
Dr. M. Manghnani, Hawaiian Institute of Geophysics
Dr. Chi-Yuen Wang, University of California, Berkeley

Seismology

Co-Chairmen: Dr. Robert P. Meyer, University of Wisconsin
Dr. Jack Oliver, Cornell University

Members: Dr. Joseph W. Berg, National Academy of Science
Dr. John Healy, United States Geological Survey
Dr. David Hill, United States Geological Survey
Dr. Mark Landisman, University of Texas at Dallas
Dr. Maurice Major, Colorado School of Mines
Dr. R. A. Phinney, Princeton University
Dr. Robert Smith, University of Utah

Related Field Experiments Other Than Seismology

Co-Chairmen: Dr. A. L. Hales, The University of Texas at Dallas
Dr. James Heirtzler, Woods Hole Oceanographic Institute

Members: Dr. David Blackwell, Southern Methodist University
Dr. Charles Cox, Scripps Institute of Oceanography, University of California, San Diego
Dr. J. C. Harrison, CIRES, University of Colorado
Dr. George Sutton, Hawaiian Institute of Geophysics

Other Participants

Dr. George Keller, Colorado School of Mines; Convenor, Electromagnetic Working Group
Dr. Arthur Kuckes, Cornell University
Mr. Charles L. Simmons, The University of Texas at Dallas
Dr. Stanley H. Ward, University of Utah

Mr. John G. Heacock, ONR Representative
Col. John K. Lerohl, ARPA Representative

Observers

Mr. H. Briscoe, Bolt, Beranek & Newman, Inc.
Mr. R. Barakat, Bolt, Beranek & Newman, Inc.

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I. INTRODUCTION

A. General

The objective of the multidisciplinary workshop was to define a program of measurement which would result in a definite answer to the question of whether an electromagnetic wave guide exists at some depth within the lower crust.

The multidisciplinary workshop was preceded by an electromagnetic group meeting at which the electromagnetic field measurements, the wave guide requirements and the need for laboratory experiments were discussed. At this electromagnetic working group meeting a program for the electromagnetic measurements was prepared. This program consisted in essence of:

(a) Reconnaissance measurements at a number of sites selected on the basis of high surface resistivity during the summer of 1972.

(b) A program of detailed study of at least the two selected sites during the summer of 1973.

(c) An assessment during December, 1973 of the results of the programs.

On the basis of the assessment in (c) a decision must be made whether the next step ought to be (1) the drilling of deep holes in the most favorable area together with an extension of the program of detailed studies to the other areas in which a crustal wave guide appears possible, or (2) the drilling of an intermediate depth hole (10-15,000 feet depth, cost $3 to 4 million) and electromagnetic measurements using sensors in this hole or (3) an extension of the pro-

gram of detailed studies before the deep holes (cost \$10 to 15 million per hole) are drilled, or (4) that the prospects of communication through the lower crust are so remote that it was not worthwhile to pursue the program any further.

The rationale of the electromagnetic program and of the wave guide possibilities have been given in full in the report by the electromagnetic working group. However, it is necessary for the understanding of the rationale of the multidisciplinary program proposed here to review briefly the possibilities of a wave guide.

Theoretical studies of the possibility of the existence of a wave guide have been reported by Wait (1971). In summary a wave guide with a resistivity of 10^6 ohm m offers a reasonable chance of communication over distances of the order of 1000 km. For a resistivity of 10^7 ohm m over a thickness of 10 km the prospect of developing communication through a crustal wave guide is good.

Estimates of the resistivity of the lower crust may be made in terms of <u>either</u> laboratory measured resistivities on the kind of material expected in the lower crust and estimated temperatures in that region <u>or</u> in terms of the resistivities inferred from electromagnetic measurements in the field.

The outlook for the wave guide is more favorable from the laboratory resistivity-temperature point of view than from the electromagnetic measurements in the field. The former will be discussed first.

Birch and his colleagues (Blackwell,1971) have shown that in several different regions of the United States the heat flow at the surface of the Earth is linearly related to the heat production by radioactive material in the surface samples. It is then possible to estimate the heat flow from below the radioactive layer and thus the temperature gradient in the lower crust. On this basis the temperatures at depths of 30 km in the Eastern United States are estimated by Blackwell to be less than 500°C. Laboratory measurements of the resistivity of natural rocks are greatly affected by the presence of water filled microcracks (Brace, 1971). Brace's resistivity depth profiles based upon the laboratory resistivity measurements on samples of igneous and metamorphic rocks suggest that the resistivity does not reach the required level of 10^6 ohm m anywhere in the crust. However, when Blackwell's temperature estimates are combined with the Brace summary values (Figure 3 of Brace, 1971) of the electrical resistivity of dry silicate rocks, it appears that 10^6 ohm m is indeed possible. Thus the question of whether resistivities permitting wave guide propagation occur in the lower crust depends on whether there are water or water vapor filled cracks in the material of the lower crust. Measurements of the P and S velocity in the lower crust show ratios of greater than 1.70 corresporresponding to Poisson's ratio between 0.234 and 0.260. The

Poisson's ratio[1] is therefore not as high as would be expected if there were water filled cracks in the lower crust. (Nur and Simmons, 1969 and personal communication, 1972).

In the report of the laboratory experiments group given in Section III it is pointed out that pyroxene granulite bodies occur at the Earth's surface. If these pyroxene granulite bodies had been formed in an environment in which free water was present, the hydrous silicate, amphibole, or perhaps a mica would have been formed instead of pyroxene. Thus the occurrence of pyroxene in these bodies makes it clear that at some time in the past dry conditions existed in the lower crust. A somewhat similar argument can be made because of the widespread occurrence of pyroxene bearing gabbros at the surface of the Earth.

The occurrence of pyroxene bearing rocks at the surface, rocks which were clearly crystallized, or metamorphosed at depth, suggests that in the geological past water free conditions existed in the lower crust in many regions. It is probable that similar conditions exist today in some parts of the Earth. Thus there is cause for optimism that the resistivity of 5×10^6 ohm estimated from the laboratory resistivity measurements summarized by Brace, 1971 (see Figure 3) and the temperatures estimated by Blackwell does occur over reasonably extensive regions of the lower crust.

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(1) Poisson's ratio $= \sigma = \dfrac{\lambda}{2(\lambda + \mu)} = \dfrac{k^2 - 2}{2(k^2 - 1)}$

where $k = V_p/V_S$

In contrast none of the resistivities so far inferred from the electromagnetic field measurements has exceeded 10^5 ohm m and most have been from five to ten times lower. The multidisciplinary working group was informed by the Chairman of the Electromagnetic working group that the inferred resistivities were probably too low for three reasons:

(1) that all errors in the field measurements tend to result in low estimated resistivities.

(2) that the resistivities inferred were average resistivities over some model averaging length and that model calculations had shown that the "peak" resistivities might be higher by from some factor between 30 and 300.

(3) that measurements had not so far been made in a region in which the surface resistivity was sufficiently high for satisfactory estimation of the resistivity at depth.

Furthermore, the measurements which are critical in respect to the maximum resistivity inferred are those at great distances for the longline resistivity measurements and at long periods in the case of other methods. Thus they are the measurements made when the limits of the observational techniques are being approached.

In view of the above considerations the consensus of the multidisciplinary group was that there were grounds for

guarded optimism that for electromagnetic wave propagation a crustal wave guide might exist. The major thrust of the programs recommended by the multidisciplinary group for the first year and a half of the program is directed towards those measurements which will determine whether that optimism is well founded.

B. Programs for years 1972-1973.

In section III on theoretical studies additional theoretical work directed towards the problem of excitation of the crustal wave guide and the effect of irregularities in the wave guide on the efficiency of the guide is recommended. It is obviously important that calculations should be made to find whether deficiencies in excitation, or attenuation due to irregularities within the wave guide or on its boundaries, are such that even higher resistivities than 10^6 ohm-m are necessary for practicable communication through the wave guide.

In section IV on laboratory studies the emphasis is on the selection of natural rock specimens free from microcracks and careful laboratory determination of the effect of pressure and temperature on the electrical resistivity, dielectric constant, velocity and attenuation. In addition it is recommended that studies directed at the determination of the nature of the rocks occurring in the lower crust should be made in favorable areas.

It is proposed in Section V (Seismological Studies) that existing seismic data on the crust should be analyzed to determine which areas are most favorable for the experiments proposed by the electromagnetic working group.

The program proposed by the electromagnetic working group consisted of reconnaissance measurements in the summer of 1972 followed by selection of at least two sites for detailed study in 1973. There are certain multidisplinary studies which must be coordinated with this program. The first of these (described in section VB2) are short (about 15 km) seismic refraction studies to determine the depth to which cracks are open in the near surface layers. These studies should, if possible, be carried out during the 1972 reconnaissance program because they are extremely relevant to the selection of the site for detailed examination. It is important also that during the summer of 1973 holes should be drilled and heat flow studies made at three or more holes in each of the areas selected for detailed study in that summer. Other geophysical studies such as gravity and magnetic measurements are also recommended for the detailed study sites.

It is apparent from the discussion in section IA that the question of how high the resistivities in the lower crust are depends in high degree on whether free water is present in the rocks of this region or not. The laboratory studies group report (Section IV) suggests very strongly that there are regions of the lower crust which were dry at some time in geological history and proposes studies directed towards the prediction of regions in which these conditions existed. It is, however, extremely important that those surface measurements which bear upon the question of how water free the rocks of the lower crust are today should be made. It appears that the most significant indicators of water free conditions are the ratio of the P velocity to the S velocity or Poisson's ratio, and the attenuation. Laboratory studies of the sensitivity of Poisson's ratio, attenuation of P and S waves and electrical resistivity, to the presence of relatively small amounts of free water have already been recommended. The logical complement of these measurements is a series of field measurements of the ratio of the P and S velocities, and the P and S wave attenuations in the lower crust. Relatively meagre information on the S velocities in the lower crust is available because S waves are poorly generated in the explosions in water or in the drill holes ordinarily used for crustal refraction studies. Suitable sources for S waves are quarry blasts and small or microearthquakes. Comparatively little work using such

sources has been done because exploitation of these sources is dependent on the use of digital techniques for positive identification of the S phase. The facilities for this identification have only recently become available to the university groups engaged in crustal research. The time has now come for S velocity and attenuation studies to be made in several regions.

The studies using quarry blasts are however limited to those regions in which large open pit mining operations are carried out. The regions selected by the electromagnetic group and/or the field site selection group may not have suitable mining operations. Thus it is recommended that a program based upon the use of a mechanical vibrator S wave source should be developed especially for use in the potentially favorable sites. The source would have wide application in the continued exploration program.

In the long term seismic methods offer the most promise for establishing the continuity of horizons over wide areas. A modest reflection refraction program is proposed for the 1972-1973 program (see Section V-D).

The low attenuation of relatively high frequency seismic waves in the oceanic crust and mantle suggests that conditions in the ocean upper mantle (to depths of 20 km) are favorable for an oceanic wave guide. A program of seismic refraction in association with gravity and magnetic measurements is therefore recommended in Section V-C.

It is also recommended that pilot studies such as those to be made in the intermediate and deep holes should be made in the vicinity of one or more existing holes in basement rocks. These studies should include studies of the change of heat productivity with depth, in situ measurement of the electrical resistivity, and seismic measurements designed to determine the rate of change of velocity and attenuation with depth.

Finally it should be noted that the tenor of the report from the electromagnetic working group is extremely optimistic that electrical methods are capable of determining whether resistivities of sufficiently high order to permit communication through a crustal wave guide exist in the areas which they regard as particularly favorable for the application of these techniques, e.g., sites with very thin low resistivity cover. The group is much less optimistic about the prospects of determining resistivities precisely in regions which are less favorable from the point of view of near surface conditions. Some part of the information which is required for the prediction of lower crustal properties in regions not suitable for the electromagnetic studies will come from the seismic programs described in Section V. However, it is regarded as important that petrologic and geological information should be assembled which will serve as a further constraint upon the resistivities to be expected at depth. Such studies are described in Sections IV and VI. These studies should be initiated during the initial program period 1 July 1972 to 31 December 1973 even if full support may not be available until a favorable site has been found.

C. Continuation of the program beyond 1973

The proposed program is geared towards reaching a decision point between eighteen and twenty-four months after the program begins. At that time there will be four options as described in section IA. If the outlook for the wave guide is favorable continuation of the project will involve three further programs which may be taken in parallel or serially. These are:

1. Studies directed at determining whether equally favorable sites exist elsewhere and how continuous the wave guide is between such sites.
2. The drilling of an intermediate depth hole (10-15,000 feet), electromagnetic experiments using sensors in the hole and other field experiments such as those described in Section VI E.
3. The drilling of three deep holes and experiments in the excitation and detection of signals from these holes.

The decision whether to proceed in parallel or serially with 1, 2 and 3 will depend in some degree on what has been learned from the 1972-1973 program. However, the main features of the programs to be followed are broadly speaking independent of whether they are being carried out in parallel or serially.

D. The continued exploration program

The electromagnetic working group considers that applications of state of the art techniques, or minor

modifications thereof, at sites at which the surface conductance is low will permit discrimination between resistivities of 10^5 and 10^6 ohm m. The group considers, however, that in order to discriminate between possible resistivities of 10^6 and 10^7 ohm m it will be necessary to make another series of electromagnetic measurements in which the sensors are emplaced in an intermediate depth hole, say 10-15,000 feet. If this hole is drilled the multidisciplinary group recommends that measurements such as those described in section VI E should be made in the hole. The cost of these measurements (other than the electromagnetic measurements) will be of the order of $100,000.

Another part of this program will be concerned with detailed studies at other sites similar to those proposed by the electromagnetic working group and in this report for the 1972-1973 program. It can be invisaged that the scale of this part of the continuation program should be at about twice the level of that carried out during 1972-1973, i.e., this part of the continuation program will cost about $\$2 \times 10^6$ per year. The techniques and procedures would be those used in 1972-1973 except insofar as these have been modified or improved as a result of the 1972-1973 experience.

The third part of the continuation program will be concerned with the extension of the inferences made at the successful site to other areas in which electromagnetic

methods may not be effective because of low resistivity surface cover. The essential features of the program are:

(a) the characterization of the potentially favorable site by means of detailed seismic and other geophysical and geological studies described in section V and elsewhere in the report,

(b) similar studies at other possible sites and comparison of the results, and

(c) less detailed profile type observations to determine how extensive areally the conditions at the successful site are and whether the potentially favorable sites are interconnected.

(d) heat flow measurements as a basis for reasonably accurate estimates of lower crustal temperatures.

(e) geological and petrologic studies which may be used with the heat flow measurements for estimates of the resistivities in the lower crust. These studies should include the regions in which communication may not be possible.

Costs for the seismic programs are given in Section V for each site. The scale of the overall program should be of the order of \$2 to 4×10^6 per year.

E. The deep hole program.

The only satisfactory proof of the existence of the crustal wave guide will be successful excitation of a signal

in one hole and reception of that signal at another. In fact because of the need to separate the effects of excitation and propagation it is necessary that three holes should be drilled. The depths to which the holes should be drilled is dependent upon the outcome of the theoretical studies described in section II. For the present it can be estimated at 5-10 km, the upper limit being determined in part by the greatest depth so far achieved in a deep hole. The cost of drilling deep holes in basement rocks is shown in Table 1. These estimates are based upon current practice and on the assumption that the sites are reasonably accessible.

TABLE I

Estimated Drilling Costs
(in millions)

Footage Depth	Days Drilling	Cost North Canada	Cost Wisconsin
10,000	200	2.2	1.8
15,000	360	3.9	3.2
20,000	610	6.6	5.4
25,000	940	10.3	8.3

The cost of the engineering to be done in the holes lies outside the scope of this report, but will probably be less than 20% of the cost of the holes. Similarly the cost of the scientific measurements like those suggested for the pilot project described in Section VI will be of the order of $\$2 \times 10^6$ for each group of three holes.

F. Field site selection

Many factors must be considered in order to select the best site for field measurement of electrical properties. Several geological factors are important. Aerial photo interpretation and reconnaissance geological mapping will be needed for each prospective site. In this study it will be important to undertake the following: (1) petrologic study of the rocks in order to adequately describe them; (2) specific petrologic study of microcracks to compare them with laboratory studies of microcracks in an attempt to determine how abundant microcracks are and how they formed; (3) observation of faults or shear zones which might provide access of water to intermediate levels; (4) observation of areas of abundant graphite, sulfides, or iron oxides which would produce low surface resistivities. We RECOMMEND that a site selection team be established with this approximate representation:

1 field man - electrical measurements

1 field seismologist

1 laboratory physical properties man

1 field geologist/petrologist

2 additional members.

It was suggested that this team consist initially of George Keller, Robert Meyer, Gene Simmons, Michael Holdaway, Ted Madden and Anton Hales.

It was recommended strongly that it should be given funds of $30 - 50,000 at the earliest possible date so that

some studies of the sites recommended for the summer of 1972 can be made before the field programs begun.

G. Management of the program

The program described in this report differs from many other scientific programs in that it is planned to reach a decision point within a fixed period of time. Yet it is a minimal cost program and does not provide for much duplication of activity, or redundancy of observation material. In consequence it is essential for the success of the program that all projects should proceed in accordance with the schedule. For this reason careful consideration must be given to the management of the program to ensure that all the essential information is in hand when the decision point is reached.

The multidisciplinary group supports the recommendation of the electromagnetic working group that a Project Manager be appointed at an early stage. It recommends furthermore that an Assistant Project Manager be appointed and that one of the managers should be knowledgeable in the field of electromagnetic measurements, the other in seismology. The multidisciplinary group recommends also that funding should be provided for two day meetings of the principal investigators at two monthly intervals. At these meetings progress would be reviewed and differences in interpretation of data explored. It is expected that this procedure will be effective in providing the setting for clear cut decision making when the decision point is reached.

Details of the operation of the Project Management team should be established in discussion with the ONR program monitor, Mr. J. G. Heacock.

II. Budget summary

The program in this report was written in the expectation that it would begin by July 1, 1972 and that the decision point would be reached by the end of December, 1973. The schedule of operations for the 1972-1973 program is written on this basis. It should be noted that the program requires two summers of field work and that the decision point will not be reached until four months after the conclusion of the field work of the second summer. Thus if the start of the program is delayed beyond July 1, 1972 it will be necessary to make changes in the schedule of operations given in Section II.

References:

Wait, J., 1971. Analytical Investigations of Electromagnetic Wave Propagation in the Earth's Crust, AGU Monograph 14, p. 315.

Blackwell, D. 1971. The Thermal Structure of the Continental Crust, AGU Monograph 14, p. 169.

Brace, W., 1971. Resistivity of Saturated Crustal Rocks to 40 km Based on Laboratory Studies, AGU Monograph 14, p. 243.

Nur, A. and Simmons, G., 1969. Earth and Planetary Science Vol. 7, p. 99 and p. 183.

The references in this section and elsewhere in the report are restricted to those giving estimates of significant parameters which have been used in the text.

II. SCHEDULE OF OPERATIONS AND BUDGET

A. BUDGET SUMMARY

July 1972 - December 1973

Management Costs	$ 280,000
Site Selection	50,000
Theoretical Studies	95,000
Laboratory Studies	
1. Microcracks and crackfree rocks	300,000
2. Electrical properties, velocities, attenuation and dielectric constant	275,000
3. Geological modeling	108,000
Electromagnetic Studies*	
1. Airborne electromagnetic measurements	100,000
2. Ground based surveys	725,000
3. ELF experiments in the ocean	75,000
Seismological Studies	
1. Existing data	50,000
2. Short refraction lines (P)	75,000
3. S studies (quarry blasts)	165,000
4. S studies (Vibrator source-short range)	100,000
5. S studies (Vibrator source-long range)	340,000
6. Microearthquake studies and seismicity	30,000
7. Preparation and reconnaissance activities	26,000
8. Reflection and refraction tudies	150,000
9. Studies at sea	300,000
Other studies	
1. Gravity and magnetics	45,000

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* These programs are described in the report of the Electromagnetic Working Group

Budget Summary continued....

2. Heat flow	145,000
3. Pilot hole	140,000
Total	$3,574,000

B. 1972-1973 PROGRAM SCHEDULE

PROGRAM		SUMMER 1972	FALL 1972	WINTER 1972	SPRING 1973	SUMMER 1973	FALL 1973
Theoretical Studies		Analysis	Analysis	Analysis	Analysis	Analysis	Analysis
Laboratory Studies							
	1	Equipment Development					
	2	and measurement	Measurement	Measurement	Measurement	Measurement	
	3		Analysis	Analysis	Analysis	Analysis	
Electromagnetic							
Studies	1	Field Measurement	Analysis	Analysis	Analysis	Field Measurement	Analysis
			Equipment Development	Equipment Development	Equipment Development		
	2	Field Measurement	Analysis	Analysis	Analysis	Analysis	
	3	As opportunity offers					
Seismological							
Studies	1	Analysis	Anal sis	Analysis	Analysis		
	2	Field	Analysis	Analysis	Analysis	Field	Analysis
	3	Field	Analysis	Analysis	Analysis	Field	Analysis
	4	Investigation	Investigation	Investigation	Investigation	Field	Analysis
	5	Development	Development	Development	Development	Field	Analysis
	6	Field	Analysis	Analysis	Analysis	Field	Analysis
	7	Investigation & Field	Analysis	Analysis	Analysis		
	8	Preparation	Preparation	Preparation	Preparation	Field	Analysis
	9	As opportunity offers					
Other Studies	1	Field	Field	Field	Field	Field	Analysis
	2	Preparation	Preparation	Preparation	Preparation	Field	Analysis
	3	Preparation	Preparation	Field	Field	Analysis	Analysis

C. Budget Forecast: Continuing Program

I.	Intermediate depth hole	$4,000,000
	Associated electromagnetic and other measurements	300,000
II.	Detailed studies at other sites (repeating the 1972-1973 program at other sites: includes electromagnetic measurements)	2,000,000
III.	Characterization of sites shown by electromagnetic methods to be favorable using seismic and other geophysical methods (for two year program)	1,000,000
IV.	Seismic and other geophysical studies at possible sites for which electromagnetic measurements are not suitable (includes heat flow measurements)	
	Continuity studies	
	For two year program	3,000,000
V.	Deep hole program (3 holes)	30,000,000
	Engineering studies	6,000,000
	Continuation of IV per year	1,500,000

These estimates are subject to revision in the light of the experience gained in the 1972-1973 program.

III. THEORETICAL STUDIES AND ENGINEERING DESIGN APPROACH

The most important engineering factor that has not been considered in previous studies is how to achieve a given current moment on the transmitting dipole. The earlier work has concentrated upon the propagation, but the total transmission loss of the system cannot be estimated until the excitation problem is solved. This will require analysis of insulated and uninsulated antennas located in deep bore holes. Anticipating that a long insulated antenna will be preferred we need to solve the boundary value problem of a coaxial (conductor-insulator without shield) cable excited at the upper end by a localized source. This solution will permit a full engineering analysis of the various factors such as length of antenna, insulation thickness, method of termination in medium and operating frequency.

An important question that needs answering is: what is the effect of the drill hole fluid on the effective moment of the antenna? Does a thicker insulation improve the coupling into the medium when we have to worry about drill hole fluid?

A closely related problem to consider is the optimum type of radiating antenna from the standpoint of minimizing the upper-over-and-down mode of propagation. For example, for a thin crustal covering layer, it may well be that the preferred path of propagation is via the surface of

the earth in a ground wave or ionospheric wave mode. By suitable phasing of the elements in the transmitting and receiving antennas we could discrimirate against the up-over-and-down mechanism. This could be an important step in our experimental feasibility studies of the earth-crust waveguide.

Finally, some attention should be paid to the great variety of possibilities for the receiving antenna. For example, it may be located on the sea floor, in which case transmission takes place vertically through the sediments. In such a case how much additional attenuation can be tolerated given the expected level of the atmospheric radio noise at the sea surface.

The theoretical studies of a layered earth in which the transitions between layers are sharp have so far shown that the crust must have a zone five to ten kilometers thick with a conductivity of less than 10^{-6} ohm m in order that ranges of several hundreds of kilometers can be achieved. In order that ranges of several thousand kilometers should be possible the conductivity must be lower than 10^{-7} ohm m. The studies have also shown that the presence of irregularities in the cross section of the channel or of transitional boundaries at the top and bottom of the channel reduce the transmission ranges.

Extension of the study of the propagation parameters in a non-uniformly stratified earth-crust wave guide is recommended. In particular the effects of discontinuities in the guiding structure should be considered so that

estimates of the energy lost due to various types of change in the cross-section of the dielectric wave-guide channel can be made. Random roughness in the wave guide boundaries should also be considered. These studies should incorporate any new information on the geometry of the low-conductivity channel in the crust obtained in the electromagnetic field measurements programs. However, precise definition of the nature of the transitions between layers is clearly beyond the scope of the electromagnetic methods. Therefore the theoretical studies should include a wide range of models based upon heat flow and petrological models and the laboratory studies of the variation of conductivity and dielectric constant with temperature and pressure.

Estimated cost, 1972-1973 $95,000

GENERAL REFERENCES

Chap. 6. Waveguide Propagation, AGU Mon. 14, 1971, and K. P. Spies and J. R. Wait, ONR Technical Reports, Nos. 1 and 2, 1971

IV. LABORATORY STUDIES

A. Introduction

Measurement of the physical properties of rocks under the controlled conditions of the laboratory has produced a set of data that is useful in the interpretation of field data gathered on the Earth. For example, consider the elastic properties. The effect of pressure on the elastic properties has been studied extensively by Hughes and colleagues and by Birch and his students in the United States and by Volarovich, Bayuk, and several others in the Soviet Union. These general features are now well-known: velocity increases with pressure but decreases with temperature, and the effect of composition can be largely accounted for by a linear relation between velocity, density, and mean atomic weight (known as Birch's law) but with several important exceptions. Undoubtedly though, much remains to be learned. For example, only recently have the effects of fluid saturation in low porosity rocks ($n \leq .01$) on the elastic properties been recognized. Surely other surprises await us.

Similar observations on laboratory measurements of such other physical properties as electrical conductivity, thermal conductivity, dielectric constant, and so on, can be made.

The study of physical properties of rocks and minerals is scientifically interesting in its own right. Yet the significance of such studies is far broader because of the use

of such data in the interpretation of field results. The relations found in the laboratory have served as constraints on the models of the crust of the Earth. Indeed, data that can be readily obtained today in the laboratory can lead to improved models of the electrical properties of the crust. How? By providing (1) a relation between seismically determined velocities and the electrical properties of the Earth, (2) a better understanding of the geochemical aspects of equilibrium conditions for hydration reactions, (3) an accurate understanding of the details of microcracks, and (4) recognition of the most appropriate rock types for dry or crack free conditions on the basis of geological-geochemical studies.

The presence of water saturated microcracks in laboratory-sized samples dominates the electrical resistivity of the samples. Whether such saturated microcracks exist in all major rock types *in situ* is still undetermined. But several independent lines of evidence suggest cause for optimism that high resistivity zones can exist in the crust: (1) Several large areas of rock, the pyroxene granulites for example, now exist at the surface of the earth that when buried in the Earth's crust in the geological past would have had mineral assemblages such that no free water could have been present in these rock masses. Furthermore, there is a high probability that the rocks now buried below these masses are still devoid of free water and have high resistivities. (2) Certain rocks, even when studied in the laboratory, are essentially free from microcracks. Examples

include diabase, some dunites, and even a particular granite (the rock-type that most commonly contains microcracks).

(3) The presence of high resistivity layers in the crust would probably not have been detected with most of the previous field measurements. The high conductivity of surface layers in the locations studied previously would have masked the presence of high resistivity zones below them.

The goals of laboratory studies on rocks in connection with the possibility of hardened subsurface communications are these:

(1) To specify the rock types most likely to have high resistivities in the Earth's crust,

(2) To specify the geographical areas that are most likely suitable for field experimentation.

(3) To determine if certain seismic parameters will be able to distinguish between the presence or absence of minute amounts of free water in a rock.

In the remainder of this section of the report, we discuss the specifics of how to attain these goals. The major contributions of this group to the solution of the present problem will be in the areas of (a) selecting those sites most likely to yield positive results, (b) estimating properties of rock *in situ* on the basis of careful laboratory studies and (c) determining precisely the values of properties of rock *in situ* by using laboratory methods in boreholes.

B. The Studies

Several different laboratory studies are urgently needed. In this section, we describe the specific requirements for them. We do not describe the way in which they should be done, however, because in most instances, either the techniques are in standard use in our laboratories at present or only minor extensions of existing techniques are needed. No major advances in techniques or equipment are required to fill the requirements of the proposed program.

1. Study of micro-cracks in rocks

The variation with pressure - and hence the variation with depth - of several physical properties of rocks is dominated by the presence of microcracks. The electrical resistivity of crack-filled granites changes by several orders of magnitude when the pressure changes from atmospheric to several kilobars, if the cracks are filled with an electrolyte and the pore pressure is kept at 1 bar.

Electron microscope techniques for studying microcracks in rocks exist. We recommend that they be used to learn when and under what conditions the cracks are generated in particular types of rocks. The goal of such studies is to develop the knowledge needed to predict reliably the location within the Earth's crust of bodies of rock that are crack-free.

The mechanical competence of a rock may involve its mineral assemblage and grain size distribution as well as

the mechanical and thermal history of the rock. Thus the search for crack-free rocks should include a study of the conditions that optimise the creation of such rocks.

The electrical properties are very sensitive to the microcrack structure and it is not really known yet how resistive very competent rocks will be. Accordingly a search should be made in the laboratory for truly crack-free rocks, and a study of the electrical properties of these rocks should be made in order to set upper bounds on the resistivities to be expected in various regions of the crust.

2. Correlation of physical properties with resistivity

The correlation of certain properties with electrical resistivity is desirable. Because of the inherent difficulty of detecting highly resistive zones in the Earth beneath conductive zones by electrical techniques, certain indirect methods become attractive. Existing laboratory data has clearly demonstrated that microcracks decrease significantly the shear wave velocities, but that P wave velocities are greatly affected <u>only if the cracks are dry</u>. Thus low P <u>and</u> low S velocities imply that a rock contains microcracks but no liquid. For such rocks the resistivity could be very high. The lunar rocks are good examples: both P and S velocities are equal to, or less than, half the intrinsic values and the resistivities exceed 10^{10} ohm-meters. On the

other hand, if only the S velocity is anomalously low, then cracks filled with fluid are present and the resistivity will be low. Thus anomalous P, S velocity ratios can be taken as an indication of fluid filled cracks. Since the resistivity problem concerns finding crustal areas with virtually no free water present, one must determine just how small a fluid content can be detected with seismic techniques.

As another example, a few existing laboratory data suggest that Q may depend inversely on the amount of water present in cracks in any given rock. Very small amounts of fluid may have pronounced effects on the mechanical Q of rock samples. However, we need to study these effects at the end of the scale of vanishing fluid content. The Q studies to date have not been done under realistic pressure conditions. We suggest that certain laboratory studies on Q and the correlation with electrical properties may contribute toward solution of the problem of finding resistive zones in the crust.

3. Measurement of electrical properties of rocks at crustal temperatures.

When high resistivity crustal zones are found, then the conditions at the bottom of the wave guide become important. Our state of knowledge of the electrical properties of rock and minerals at crustal temperatures (300-600°) is still poor. The existing data are not consistent and there is very little knowledge concerning the mechanisms of conduction. We recommend therefore that the electrical properties of suitable rocks be measured under conditions in the laboratory that simulate those that exist in the crust. Correlation with seismic properties is also desirable.

4. Geologic and petrologic studies

Of great importance is the need to arrive at reasonable inferences as to the common rock types expected in the deep crust. Seismic data for the areas under consideration may leave several rock compositions possible. It is proposed to construct models constrained by geophysics and geochemistry to determine those rock types compatible with both geophysical data and geological observations in the electrical test areas and elsewhere. Samples of deep crustal rocks below several areas of North America are provided in diatremes and in deeply eroded crystalline regions. One can usually estimate the pressure of formation of

such rocks from mineral stability data as well as geological and geophysical data from their localities of occurrence. Then using the knowledge of rock types commonly found at deep crustal pressures, geophysical data, and surface rock types at the proposed sites, one should be able to predict adequately the rock types likely to be encountered at depth.

Many areas now exist in which the mineral assemblages and the temperature-pressure conditions are such that free water should have been removed from the system by hydration reactions. Reaction rates, however, in some areas may prevent the system from reaching the equilibrium conditions. Reaction rate studies applicable to a geologic time scale involve some rather large extrapolations, but such information could, with some knowledge of the time-pressure history of the crustal zones form the basis on which to predict the presence or absence of free water in those zones. Clearly the presence of dry, open microcracks in rocks would not lower the electrical resistivity. Recall the lunar rocks with many cracks but resistivities greater than 10^{-10} ohm-meters. Thus the accurate prediction of the absence of free water at depth on the basis of geochemistry may suggest high resistivity zones even in rocks that contain microcracks.

C. Priorities

We do not list priorities for the work suggested in this program. The usual critera for arriving at a list of priorities would include these--(1) significance of the likely contribution toward the solution of the problem, (2) relative ease of accomplishing the task, and (3) availability of standard, or almost standard, techniques. All of the tasks that we recommend have roughly equal priority. We have included only those items that we believe likely to contribute significantly towards the solution of our problem. All of them can be done with standard, or with minor adaptations of standard, techniques. We could have added five additional tasks that would have been relevant but of lesser priority in order to show the present set as having very high priority in a longer list. We have chosen to recommend only those tasks with very high priority.

D. Manpower and funding requirements

Several groups in the U.S. academic community are capable of making significant contributions to this potential program. In this section, we outline briefly by tasks the total manpower and funding requirements. In the man-power column, we have included only the professional people (geologists, geophysicists, engineers, and so on) but funds are included for non-professionals as well. The time needed for these studies is 3 years. If an 18-month program is desired, then the cost is about 2/3 that of the recommended program and the results are something less than 1/2.

	Funds ($1000)	Man-Months
Studies on Microcracks	310	40
Experiments related to drill hole Sites (6MM/site x 3 sites)	200	18
Laboratory studies of rocks	275	54
Site Selection (2 main sites & pilot project site)	90	15
Geological Modelling of North America Crust	105	20
GRAND TOTAL	$980	147MM

V. SEISMOLOGICAL STUDIES

A. Introduction and justification

Although the basic measurements necessary to determine the possibility of existence of extensive electromagnetic waveguide conditions in the earth are electrical, seismic measurements can provide valuable support of the electrical measurements in at least two major ways.

First, measurement of deep electrical properties from the surface requires surface conditions (high resistivity) that exist in only a few areas. Extension of the results of electrical measurements to the large geographic areas involved in practical communications systems can only be done using non-electrical geophysical measurements. Seismic measurements are capable of exploring the continuity of sub-surface conditions under a much wider variety of surface conditions.

It is generally agreed that the presence or absence of free water controls the resistivity of rocks, both near surface and in the deep crust. Laboratory measurements have shown that the velocity of P waves is lowered by the presence of cracks within the rocks. If the cracks are completely filled with water the effect on the P velocity are small and may be difficult to detect. In spite of this possible difficulty in interpretation the electromagnetic group pressed for short detailed seismic refraction surveys to be undertaken during the reconnaissance period.

In the case of S waves the velocity is substantially lower even when the cracks are waterfilled. Thus it would

be desirable to conduct short detailed S refraction profiles. The difficulty is the source. Mechanical vibrators exist (Cherry and Waters, 1968) which would serve as shear energy generators and a program of study using mechanical sources is recommended.

Insofar as the deep crustal rocks are concerned the laboratory measurements suggest that the presence of water under high pore pressures is again most easily recognized by low shear velocities. At high pore pressure, the P velocity is affected much less than the shear (S) velocity. Thus the ratio of the P and S velocities, or Poisson's ratio, is a reasonably sensitive indicator of the pressure of water in the deep crust. If large mining operations occur in the region these provide a suitable source for S wave studies. In most of the sites provisionally selected for the electromagnetic study this possibility does not exist. If microearthquakes occur in the region it is possible to estimate the S velocity. On the other hand, if the microseismic activity is sufficiently high for S wave studies that region might be unsuitable for the electromagnetic studies. The solution lies in the use of a mechanical shear wave energy generator. This forms part of the recommended program. It is possible that it will be necessary to develop larger shear wave energy generators for lower crust refraction profiles than currently exist.

In view of the importance which attaches to the determination of the properties of the lower crust and especially

of those properties other than the electrical resistivity which are influenced by the presence of free water within the lower crust it is recommended that S wave refraction studies should be undertaken in regions where suitable quarries or large scale mining operations exist.

During the site selection and the design of the detailed site exploration plan, a seismic reconnaissance survey can protect the project from selection of an anomalous site or a survey line across a locally disturbed area.

The seismic program consists of three parts:

(1) measurements & studies to be started during the reconnaissance period

(2) measurements at the site selected for detailed study

(3) measurements aimed at extending the results of the electrical measurements program to the large geographic areas involved in practical communications systems.

B. Program for 1972-1973

1. Compilation of existing data

Evidence bearing on the continuity of electrical wave guides in the earth crust must come primarily from seismic data.

In the past 15 years about 50 good seismic refraction profiles have been recorded in the continental United States and much of this data is recorded in analogue form on magnetic tape. These profiles have been interpreted at different times by many different people using different reduction techniques and as a result the data is not available in an easily accessible format.

In a nine month program very significant progress could be made in reducing an identical record section format which could then be used for a systematic region to region comparison of similarities and differences in the earth's crust.

Initially emphasis should be on quickly compiling a catalogue of potentially available data. A large portion of such a list already exists. (See Figure 1 and appendix). Next estimates of reduction expense would be assembled from the holders of the data for the profiles judged most critical. Production of standard formatted digital tapes and record sections would proceed presumably principally at the institutions taking the data as they retain the details of the experimental parameters.

All the institutions playing a major part in the taking of the data are equipped for digitization and processing to a common format record section. Their geographic distribution is such that they could act as regional centers for processing of other critical profiles by cooperating institutions not so equipped. We would propose Canadian institutions be approached as regards this effort and their participation be encouraged.

The assistance rendered for digitization and hence toward digital analyses makes likely widespread cooperation.

Estimated cost: $50,000 for the period 1 July 1972 to 31 December 1973 (30 man months plus computer).

2. Short range seismic refraction studies

Near surface basement rocks often show significantly lower velocities at short distances (less than 15 km) than at greater distances. These lower velocities are attributed to the presence of microcracks filled or partially filled with water. These cracks have a considerable effect on the near surface resistivities. The electromagnetic working group places considerable emphasis on the selection of sites in which the near surface zone of low resistivity is either not present or as thin as possible. It is proposed therefore that short range seismic refraction profiles should be observed at about ten points in each of the areas to be reconnoitered as possible sites for the detailed electromagnetic and other studies. The experiment should include $dT/d\Delta$ determinations across an array of fixed receivers or across an array of shots

at repeated locations. This isolates changes in the weathering correction under the element changing range. In some areas it will be possible to use airgun sources in shallow lakes. In others such as the Canadian Arctic plastic explosive pads are probably a suitable source. Shot sizes would be small, not more than ten pounds. The alternative sources are the various types of mechanical source used by the exploration industry.

This part of the program is concerned with measurements of the P wave velocity. If a mechanical shear wave energy source is used as well the significance of the contribution to the program would be greatly increased.

Estimated cost (for the period 1 July 1972 to 30 March 1973): $25,000 per region reconnoitered except in the Arctic

$50,000 for an Arctic region.

3. Studies of S wave velocities using quarry blasts

Laboratory studies show that the S velocity is more affected by water filled cracks than the P velocity (Nur and Simmons, 1969). Laboratory measurements of the electrical resistivity of dry silicate rocks are all greater than 5 x 10^6 at temperatures of 500°C (Brace, 1971; See Figure 3). Thus if the rocks of the lower crust are water free suitable conditions for an electromagnetic wave guide exist. Few precise values of the ratio V_P/V_S have been determined for the lower crust. Measurements of P and S waves through the lower crust yield ratios ranging from 0.234 to 0.260. The determination of this ratio is most important for this project. In general the seismic amplitudes of S waves from quarry blasts are four or more times those

of P at short distances. These events therefore can be used for the determination of the S velocities in the lower crust (and incidentally also the Sn velocity). The major problem in earlier work, namely the certainty of identification of the S phases, is no longer serious for digital processing of the records permits of reasonably good identification of the S phases. It is recommended that a program of S wave measurements should be carried out in all regions where large quarry blasts are available.

Estimated cost: $165,000

References:

Nur, A. and Simmons, G., 1969. Earth and Planetary Science Vol. 7, p. 99 and p. 183.

4. The use of a shear wave energy source in near surface field studies.

Cherry and Waters (1968) have described the use of a mechanical or mechanico-hydraulic source for shear wave studies down to depths of the order of 10,000 feet. The results quoted by these authors, and more extensive measurements reported by Erickson, Miller and Waters (1968) showed that the ratio V_p/V_S is of order 2 to the depths covered by these measurements. A ratio of V_p/V_S of 2 corresponds to a Poisson's ratio of 0.33. These result were obtained in sedimentary rocks in Oklahoma. They can be interpreted as confirmation of the result described earlier in the section on laboratory studies that in water filled rocks the ratio V_p/V_S is high. Thus seismic surveys using this type of

source would be invaluable in determining whether near surface rocks are water filled or not, and also in determining the depth to which water filled cracks persist below the permafrost zone at the Arctic sites.

Estimated cost of an experimental program $100,000

References:

Cherry, J. T. and K. H. Waters, 1968. Geophysics, Vol. 33, p. 29

Erickson, E. L., Miller, D. E. and Waters, K. H., Geophysics, Vol. 33, p. 240.

5. Longer range S studies using a mechanical source.

It is doubtful whether the existing sources are sufficiently large for refraction surveys to the distances of 100 to 150 km necessary for the determination of seismic velocities in the lower crust. In fact, so far as is known, little refraction work has been done with these sources. However, these studies would have prime importance in determining whether water free rocks exist in the lower crust in areas where low surface resistivities made it impossible for the electromagnetic methods to achieve the necessary resolution. Thus a program for the development of a large source, or adaptation of existing sources for refraction studies, and for field tests in the detailed site locations during the summer of 1973 is recommended.

Estimated cost: $340,000

6. Other studies

A number of the studies recommended in Section IV-C could be applied in the reconnaissance study if time and funds permitted, especially those dealing with reflection-refraction surveys, passive methods and seismicity studies. It is recommended that wherever possible microearthquake listening posts be established in the areas reconnoitered for two reasons: First to characterize the tectonic state of the region and second as a source of S velocity depth information. Reconnaissance studies can also be carried out using existing arrays across the country.

Estimated costs: 1972-1973	1.	Reflection and refraction studies	$150,000
	2.	Preparation and reconnaissance	26,000
	3.	Microearthquake and seismicity	30,000

Note: These are limited programs and not the full scale programs described in Section IV-C.

C. Studies at sea

Indirect evidence indicates that if an electromagnetic wave guide ($\rho > 10^6$ ohm m) exists anywhere within the earth above 20 km depth there should be one near the base of the oceanic crust (lower crust - or uppermost mantle):

(1) P_n velocity 8 km/s and S_n velocity 4.7 km/s giving a Poisson's ratio of about 1/4, at the pressures existing at the depth of the Moho under oceans all point to relatively low temperature and low free fluid content;

(2) Long range high frequency propagation of P_n and S_n under the oceans (frequencies of about 8H_z observed to distances of several thousand km) indicate a high mechanical Q for sub-Moho materials (perhaps several thousand) - also pointing to low temperatures and low free fluids.

Detailed seismic, gravity, magnetic, and heat flow surveys are relatively easy to conduct at sea. However, the direct measurement of zones of high resistivity beneath the highly conducting ocean from near the ocean floor is difficult if not impossible.

Detailed seismic studies, aimed especially at determining P/S ratios (Poisson's ratio) and Q (mechanical), when combined with laboratory data and reliable estimates of petrology may provide the best means for estimating the electromagnetic properties beneath the ocean. The seismic program at sea is similar to that described for land. Ocean bottom

seismographs, using H.E. explosives and repetitive sources can provide information on both P and S velocity situations. A 100 x 100 mile area could be covered in considerable detail in one month of field work in an ocean basin, (for example half way between west coast and Hawaii or the Atlantic). Gravity magnetics and heat flow measurements would be made along with the seismic work to provide additional constraint on the interpretation.

Estimated cost including data reduction: $300,000

(includes $180,000 for ship time)

D. Measurements at the sites selected for detailed study

1. Reflection-refraction studies

a. Introduction

Seismic detailed profiling is recommended in support of determining subsurface structure essential to the electromagnetic objectives. A seismic profile is capable of yielding detailed and continuous cross-sectional structure in terms of the following parameters:

(a) P-wave velocity

(b) S-wave velocity

(c) Q

(d) Inhomogenities in the impedance gradient

The precision and resolution of these determinations are strongly dependent upon the observational density of the field data collected.

The structure of the crust to a depth of 25 km can be determined with an average resolution of 2 km and a P velocity precision of 0.2 km sec. The shear wave structure is correspondingly determinable with a resolution of 4 km and a velocity precision of 0.4 km sec. Attenuation estimates to 10 km depths regions may be made, with a precision in 1/Q of .0025.

Narrow angle reflections are produced by backscattering from "lumps", gradients and discontinuities in the acoustic impedance. A compilation of this data gives a two and with area coverage a three dimensional structure model which in turn provides a basic structure for the superposition of other geophysical model parameters.

For a total program as is recommended the following are required:

- Reconnaissance and preparation pre-study
- Four basic profiles in each recommended EM study area
- Surface and body wave spectral studies (see Section 4).

b. Recommended program

1). Preparation and Reconnaissance activities: (June 1971 to March 1973)

These are modest activities which would normally be conducted by coordinated investigative groups with some minimum manpower commitments.

a) Acquisition, playback, and compilation of existing deep crustal reflection data. This material is present in unknown quantity in the oil companies. Personal contact, with support from the program, is is the most effective way of obtaining this data but it should be sought under the unified sponsorship of the ONR-ARPA program.

Costs: Travel and partial support of post doctoral investigator: $4,000

Playback & compilation: $6,000

b) Special recording runs to improve methodology. The major aim would be to obtain Vibroseis (or equivalent) data for deep

crustal penetration.

Costs: One recording week and 2 months of investigation: Salary, travel and analysis $20,000

2). Recommended Surveys, EM sites (March to December, 1973)

a) General considerations:

In this section, we describe the recommended profiling, including coverage, effort required and cost. Four possibilities have been considered. These are:

(1) Reconnaissance refraction and reflection study
2 crew weeks
one line of section - 75 km, discontinuous coverage
Est. cost: $30,000

(2) Detailed full line coverage profile
6 crew weeks
one line of section - 150 km
Est. cost (field & analysis): $90,000 - $100,000

(3) Area coverage: 4 interlocking profiles
24 crew weeks
4 lines of section - 150 km each
Est. cost: $347,000 - $466,000

(4) Multiple coverage common depth point survey.

Commercial crew @ \$10,000 per line mile

$\$10^6$ per 150 km line; 4×10^6 per area (4 profiles)

A reconnaissance survey (1) can add to an otherwise blank data base, but is of dubious value in providing hard constraints related to the electrical structure of the crust. The single profile (2) gives the desired precision but lacks area coverage. The recommended survey (3) provides the information sought and described in the opening paragraph. It does not provide the interval velocity data obtainable from (4).

The recommended survey is to be conducted in the special test area designated for the EM studies. It is to be conducted by a coordinated crew from a small (2-4) group of universities. (This is the only way the costs can be kept as low as they are). It is to be carried out in the period March-September, 1973, following the period of preparation and reconnaissance.

Survey configuration

1) Basic profile

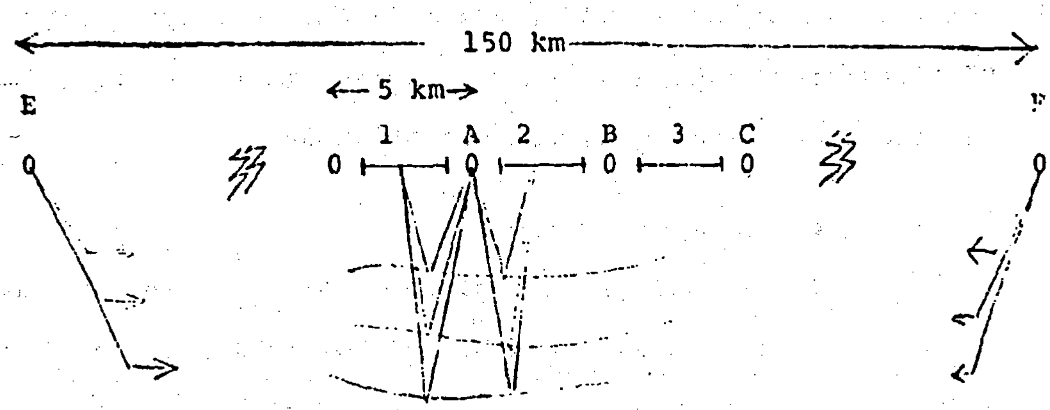
The recommended basic profile is made up approximately as follows: Shot points spaced at 5 km intervals embrace a total aperture of 150 km.

```
0     0     0     0     0     0     0 ...................
------------------------------------- ...................
(                  150 km                              )
```

Each reflection shot point will involve a minimum of one shallow 6 hole pattern which is fired either one hole at a time or with 2 to 6 holes simultaneously with about 50# of high explosive in

each hole. Cost in easy to moderate drilling country is $1000 per loaded shot point. Additional holes at the profile ends will be charged with up to 200# for repeated refraction shots.

2) Profile Coverage: Assume that the shot at A is in the middle of the profile with receiver arrays at 1 & 2.

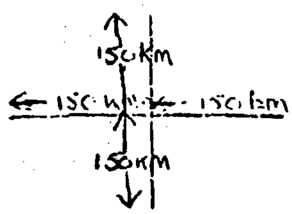


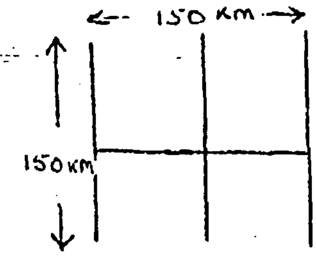
The shot pattern at A is fired to get reflection coverage under receiver spreads, 1 & 2. The large shots at E and F are fixed and give refraction and wide angle reflection coverage. The spread at 1 moves to 3 and B is fired. The spread at 2 moves to 4 and C, E, and F are fired, etc. The maximum depth of refraction coverage is 25-30 km. The reflection coverage is best for 5-25 km depths and adequate to marginal coverage is realized for 25-50 km depth.

Effort: Two crews of 4-6 men each. Allowing an average 1-1/2 days per setup = 45 crew days.

Field cost only:	Drilling and loading holes	$45,000
	Crew time and contingencies	30,000
	Total field cost per 150 km profile	$75,000

3) Areal Coverage: Four profiles in either geometry shown below:





The latter gives more intensive, three-dimensional coverage. Total field effort 4 full profile lines: $300,000 using 2 crews. Elimination of full reflection coverage near the ends of lines results in an economy version at $250,000.

c. Instrumentation

Two single truck digital recording units are needed. Basic procurement cost would be $25,000 to $30,000 per rig. Modifications to existing equipment, mainly for analogue and digital compatability could be done for about $10,000 per unit.

New: $60,000 total

Modified: $20,000 total

d. Costs

1) Staff Personnel costs: (including overhead)

2 Digital technicians or engineers (year)	$40,000
4 grad students (year)	32,000
3 faculty salary months	12,000
(Two institutions)	$84,000

2) Data reduction costs on an interactive computer

Disc equipment lease	$ 5,000
Time	10,000
Programmer	12,000
	$27,000

3)

Total Costs:	Minimum	Recommended
field	$250,000	$300,000
instrum.	20,000	60,000
personnel	50,000	84,000
analysis	27,000	22,000
	$347,000	$466,000

Remarks: The recommended program amounts to a special area survey which takes advantage of known body wave propagation phenomena in crystalline rocks.

1) Refractions give average velocity vs. depth, continuity and dip of interfaces.
2) Critical angle reflections and other second arrivals localize the gradient or interface regions' configurations and determine something of the sharpness of gradients. Following the arrivals as a function of position and time provides 2 or 3-dimensional structure.
3) Narrow angle reflection (back scattering) gives detailed structure and is sensitive to local heterogeneity. The final product is an acoustic cross-section, similar to the results of airgun work at sea.
4) Non-explosive sources (e.g. Vibroseis) could cut overall cost. The preparatory work the first summer should determine its feasibility.

5) There is special need for horizontal receivers for S wave identification.

6) Operations in difficult near surface conditions may increase shot costs such as to make Vibroseis mandatory.

7) Accurate P and S wave interval velocity distributions from multiple coverage reflection data can be used to determine distributions of elastic properties. Poisson's ratio may be obtained with a resolution of 0.05. More importantly, these interval velocities can provide estimates of water saturation as a function of pressure (depth). These parameters provide the most detailed determination of wave properties with existing seismic sources and digital recording. Less detailed velocity distribution can be obtained from refraction and wide angle reflection for layers as thin as 5 km.

If the requirements of the EM survey include detailed internal velocities at all points along profile, then the multiple coverage common depth point reflection methods used commercially are needed. The cost of these contract services is about \$10,000 per line mile, or $\$10^6$ per profile, or $\$4 \times 10^6$ for four.

A CDP survey along 20 miles of line would give good interval velocities at one point - say the center of the area. This would be a \$200,000 increment to the recommended reflection-refraction survey.

Site factors:

8) Costs estimated for the different types of survey are based on the assumption that field conditions are optimum. This includes:

- easy vehicular access - flat ground
- easy drilling for shots

The high plains areas and intermountain plains of the Western United States best qualify. Increased logistical difficulty means increased costs. For shield areas like Wisconsin, drilling costs would increase by 50%. For inaccessible areas requiring helicopter transport, total costs would probably increase by a factor of 3.

d. Project management

A full time scientist manager is required to coordinate activities, handle finances, legal problems, etc. This person should be on the staff of the overall project manager.

2. Passive seismic experiments

Passive seismic experiments, including studies of body waves and surface waves from natural sources, can contribute a large body of quantitative information about the few specially selected sites chosen for intensive geophysical study. These passive experiments, combined with the active and passive electrical studies, with reflection and refraction measurements, potential methods such as gravity and magnetic mapping, and studies of Q, seismicity, heat flow, well logs, and regional geology, ought to produce a picture of the crust rivaling many of the better areal studies in the literature.

The passive experiment can provide measurements of P and S wave velocities, Q from body wave studies of natural sources, P and S delays in the crust and underlying mantle, the crustal transfer function of long-period body waves and the tilts and displacements produced by atmospheric loads. But perhaps the most diagnostic experiments will come from the observation, identification, separation, and interpretation of multi-mode seismic surface waves. The resolution which these permit should lead to detailed velocity and thickness estimates for all of the major crustal features, including Q as well as velocities along with estimates for the uncertainties of all the desired parameters, since it has been demonstrated that the errors of measurement may be propagated into error

estimates for the resulting models. The P and S refraction velocities and reflection times should serve as powerful constraints on the resulting solutions. Gravity and magnetic information may also be integrated into this process.

The observations should be based initially on available data from the WWSSN and Canadian networks for the first-look reconnaissance, but the really detailed studies can only result from the implementation of an array of seismometers and microbarographs. This array, covering from five to nine sites for an area of 400 x 400 km, ought to have at least long-period vertical component capability. Optimally, 3-components and microbarometric sub-arrays of 3 or 4 sensors, successively deployed at each site, might be used. The orientation of the array, if chosen with regard to most active source regions and local geology, would produce useful data within the short time envisioned (1 to 1 1/2 years). Telemetry, wide dynamic range amplifiers, gain-ranged digital recording at a central recording site, and efficient means for processing the data are all required for optimal recording of events of large and small magnitude. A cheaper route would involve the use of conventional drum recorders and digitization of events of interest.

CONVENTIONAL PASSIVE SEISMIC

BUDGET

A1.	5 to 9 Vertical Units \$3,000/site (Additional units @ ≈\$3K/channel) up to 27 units + 12 μ-barographs	\$15 K to \$27 K
B1.	Computer Time	\$10 K
C1.	⅛ Scientist, 1 Post-Doctoral Man, 1 Student, Record Changers	\$20 K +Overhead \$14 K
D1.	Field Expenses, Travel, Misc.	\$10 K
		\$7 K to \$85 K

(First Year Labor & Overhead ≈\$40 K)

GAIN-RANGED PASSIVE SEISMIC

BUDGET

Minimum

A1.	5 to 9 Vertical, LP Capability,	\$3,500 ea.
	Wide-Dynamic Range Telemetry	\$17,500 to \$31,500
	(Optimum: 3 Components/Site	
	+ 12 μ Barographs @ ≈3500 ea)	
B1.	Gain-Ranged Digital Recording	
	Facility [incl. recorder & playback	
	@ ≈\$20 K each]	\$65 K
B2.	Computer Time	\$10 K
C1.	½ Scientist, 1 Post-Doctoral Man,	\$35 K
	1 Student, Engineer	O'Head \$27 K
D1.	Field Expenses, Travel, Mis.	\$10 K
		\$170 K
		40 K
	First Year Labor & Overhead	\$210 K
	Minimum (Vertical Component Only)	

(Optimum with 3 component instruments \$350 K)

3. Seismicity studies

The seismicity associated with a given region provides valuable clues about the physical properties at depth within the region. In particular

(1) The three-dimensional distribution of earthquakes occurring in the region can be established from data recorded on an array of short-period seismometers that spans the region. Those same data can be used to construct "vertical" travel time curves for earthquakes at a range of depths. This approach, for example, has been successfully used in t. USSR to define low-velocity zones in the crust.

(2) Amplitudes of arrivals recorded at a range of distances from earthquakes at a range of depths can in principle be used to untangle geometric propagation effects from intrinsic attenuation (Q) effects. Such data offer reasonable hope for estimating Q as a function of depth within the depth range occupied by earthquakes.

(3) Where they exist, earthquakes provide direct evidence for cracks and fractures in the crust. Furthermore, the existence of earthquakes at even moderate depths probably indicates the presence of interstitial fluids at relatively high pore pressures. This, in turn, probably implies a relatively low resistivity to depths at which the earthquakes occur.

We recommend that seismicity studies be undertaken with these objectives in mind for the special sites as well as a reconnaissance tool. Existing instrumentation and techniques can be used to accomplish this goal.

For the special site first stage investigation should involve between 15 to 30 portable, short-period instruments distributed over the site to monitor seismicity for a period of 2-3 months. Cost ≈$32,000.

4. Attenuation studies

In most seismic studies velocities and structure receive primary attention; attenuation is usually a secondary consideration and is frequently ignored completely. Yet attenuation is perhaps more closely related to the rock properties of interest for an electromagnetic wave guide than are other seismic parameters. Attenuation may depend, for example, upon temperature, partial melting, heterogeneity, and water content. Unfortunately, it is not always possible to separate these effects, but the measurements are of value, nevertheless. For example, in thinking of an electromagnetic wave guide that might span the North American continent, is it irrelevant to know that crustal seismic waves are <u>much</u> more strongly attenuated in the west than in the east? Almost certainly not. But only the gross details of the spatial attenuation patterns are known. Studies aimed at somewhat finer detail and using existing data should be carried out with the goal of providing maps, first of the U. S., then North America, and ultimately of other continents and the oceans showing spatial variations of seismic wave attenuation in the crust.

Eighteen month study - $60,000.

E. Extension of the Measurement Program, 1974 Onward

At this stage the emphasis will be on determining the continuity of the wave guide over large geographic areas. Seismic measurements combined with magnetic and gravity measurements offer the most promise for they are relatively less seriously affected by surface conditions than the electromagnetic methods. Essentially the program consists of detailed seismic studies in the potentially favorable sites, comparison of similarly detailed measurements at other possible sites selected on the basis of geological or geophysical information and similar studies along profiles radiating from and interconnecting the favorable sites. The methods to be used are those outlined in Section IV-B.

The cost is estimated to be \$1.5 x 10^6 per year.

VI. OTHER MEASUREMENTS ON LAND

A. Geological studies

The search for an electromagnetic wave guide in the crust involves rocks solely of pre-Cambrian age. A thorough review and study of the pre-Cambrian geology of any special site will be essential for optimum utilization of seismic and other geophysical data - including the electromagnetic observations.

The renewed interest and enthusiasm for pre-Cambrian geology that has sprung from the application of the plate tectonics theory to rocks of this age, and especially of late pre-Cambrian age, is a clear indication that major advances in our understanding of deep crustal rocks are soon to be achieved. Our ability to predict what rocks may be found at depth in the crust may improve remarkably over the next few years. ..uch information would be of immediate and crucial value to the electromagnetic wave guide p ject.

A small number of geol... s, say 2 r 3, working on this topic, surveying the literature and interpreting the geophysical data with geophysicists should be supported with the goal of preparing maps or other illustrations of pre-Cambrian sub-surface structures, rock types and other information insofar as possible and as it may relate to the wave guide problem.

Cost for period 1 July 1972 to 31 December 1973: $75,000

B. Gravity and magnetics

Various kinds of geophysical data, particularly gravity and magnetics, in addition to seismic information, will be useful in selecting sites or paths for study or application of wave guide propagation. During the initial exploration phase of this project, additional measurements will be needed at the special site areas if the existing coverage is inadequate. It is recommended also that data should be compiled and maps prepared or assembled for a report on the prospects of wave guide propagation elsewhere than at the special sites.

Estimated Cost of compilation from 1 July 1972 to 31 December 1973:	$15,000
Estimated cost of additional measurements where necessary:	$25,000

C. Heat flow studies

Excluding the effect of pore fluids, the temperature of a rock is the most important factor bearing on the resistivity of the crust and upper mantle. Temperature certainly is the factor controlling the depth to which any layer of high resistivity extends and is important in evaluating the maximum resistivity reached in the crust. It is not important in determining the resistivity of the upper crust. Crustal temperatures are a function of the heat production of the continental crust, heat flow from the mantle, and the thermal conductivity of the crust and upper mantle. From measurements of sur-

face heat flow and surface heat production of U, Th, K at several (3 or more) locations in a given area (of several thousand km^2) the first two quantities can be determined (Birch, Roy and Decker 1968, Blackwell 1971). The thermal conductivity can only be inferred from measurements on postulated lower crustal and upper mantle analogues. Nonetheless given surface heat flow, thermal conductivity and U, Th, K content temperatures in the crust can be calculated to a precision of $\pm 50°C$. These temperature depth measurements can be combined with laboratory measurements of electrical resistivity to estimate the upper boundary of the conductive region of the mantle. This boundary then can be used to constrain interpretive electrical models from EM experiments. The data can also be used to evaluate the possible upper limit on the resistivity of the wave guide itself in the absence or presence of pore fluids (Brace, 197.).

It is specifically proposed that in the second and succeeding years of the program, at least three or more holes be drilled for heat flow at each of the sites selected for detailed studies by the electrical methods. The holes will be core drilled in rocks of varying heat production from U, Th, and K so that the distribution of heat production in the crust and the mantle heat flow can be measured (see Roy et. al., 1968, Blackwell, 1971). Concomitant measurements will be made of the temperature, thermal conductivity of the rocks, and radioelement con-

centration. The holes might be logged by various techniques to furnish ancillary information, such as in situ resistivity and the cores would be available for laboratory measurements of electrical resistivity, etc. The temperature on holes would be measured one month after drilling but would be cased and maintained for at least a year so that they could be remeasured after a year to ensure that the effects of drilling on the temperature had been negligible.

If the locations of the sites for detailed study are in the Canadian Arctic, drill holes of the order of 400 meters will be required to get below the effects of recent changes in the surface temperature (see Beck, 1965). Drill holes of 2-300 meter depths might suffice in localities further south.

The estimated cost of the heat flow studies is about $50-100,000 drilling cost per EM site and $50,000 for laboratory measurement, travel and data reduction. The drilling cost is, of course, dependent upon the location and the depth of hole required by the site history.

References:

Blackwell, D. D., 1971. The thermal structure of the continental crust in The Structure and Physical Properties of the Earth's Crust, AGU Monograph 14, John G. Heacock, Editor.

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Birch, F, R. F. Roy and E. R. Decker, 1968. Heat flow and thermal history in New England and New York in Studies of Appalachian Geology: Northern and Maritime edited by E-an Zen, W. S. White, J. B. Hadley and J. B. Thompson Jr., Interscience, New York

D. Pilot deep hole measurement project

Some of the principal uncertainties in assessing the potential of a wave guide in the lower crust arise from the need to infer the changes in the physical parameters of rocks at depth from physical measurements at the surface or in the laboratory. It is appropriate therefore to propose that a program for the measurement of geophysical parameters should be carried out in existing holes in basement rocks in Oklahoma. It is planned:

(1) to measure the following parameters in the hole: heat flow, electrical resistivity velocity of elastic waves

(2) to provide sidewall cores for electrical resistivity, heat productivity, velocity, petrologic and geochemical measurements in the laboratory

(3) to compare the results of sonic logging with the results of velocity and attenuation measurements to a seismometer and/or hydrophone string in the hole from shot points at varying distance from the hole and with good azimuthal distribution.

The hole selected for the pilot study is:

the Phillips-Matoy Well I in southeastern Oklahoma drilled to a depth of 12,500 feet in granite

Estimated cost: $140,000